LOOKING FOR SOURCES OF AN OPHIOLITIC MÉLANGE: THE CASE OF RHODES (DODECANESE, GREECE) AND ITS TIES WITH EASTERN MEDITERRANEAN UNITS

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ABSTRACT

The ophiolites and related mélanges in the Eastern Mediterranean region are important proxies for tracking the geodynamic evolution of the Paleotethyan and Neotethyan basins. Along the Aegean forearc, the island of Rhodes (Dodecanese, Greece) is located at a key position between the western and eastern ophiolites of the region and exposes an ophiolitic mélange unit ("Kopria Mélange") comprising sedimentary and magmatic rocks of Paleozoic and Mesozoic ages, but no clear understanding of their relationships. New micropaleontological results obtained on radiolarian cherts show that some blocks in the mélange are Middle Jurassic (early Aalenian), Late Jurassic (late Kimmeridgian), and Early Cretaceous (Valanginian; late Valanginian-early Aptian) in age, complementing previous data obtained on blocks with sedimentary and magmatic sources (Early or early Late Carboniferous to Late Cretaceous). The mélange components age range (MCAR) of the Kopria Mélange, a new indicator corresponding to the time span represented by all the elements in a given mélange, reaches a significant duration of 239±9 million years. A review of the nature and ages of the Kopria blocks shows that the mélange is probably polygenetic and could record 1) Paleozoic units derived from the southernmost part of the northern Paleotethyan margin; 2) the local Prophitis Ilias Unit traditionally associated with the Pindos Zone *s.l.* of continental Greece, Peloponnesus and Crete; and 3) potential remnants of the sedimentary cover of the Rhodes ophiolite. It is difficult to determine whether the mélange formed exclusively during obduction or was related to subduction-accretion processes associated with stacking of upper and lower plate components. However, the co-occurrence of ophiolitic blocks with Jurassic and Cretaceous ages reveals a double magmatic signature which could represent the transition between units comprising the Middle-Late Jurassic ophiolites traditionally associated with the Hellenides, and the Cretaceous ophiolites correlated with the Taurides (Lycian Nappes). These results show that the ophiolitic mélange of Rhodes possibly records sources from two distinct and diachronous parts of the Northern Neotethyan basin.

INTRODUCTION

The ophiolites and related mélanges in the Eastern Mediterranean region provide essential clues for the reconstruction of the geodynamic evolution of the Paleotethyan and Neotethyan basins. The island of Rhodes, located in the Dodecanese archipelago, belongs to the Aegean forearc along the Eurasian-African plate boundary (Fig. 1) at the junction between two important ophiolite domains of the Alpine realm *s.l.* (western domain: Dinarides, Hellenides; eastern domain: Taurides, Cyprus; Robertson, 2002). This tectonic setting has been the subject of a number of studies seeking to establish geological links between Greece and Turkey (Aubouin and Dercourt, 1970; Leboulenger and Matesco, 1975; Hatzipanagiotou, 1988; Koepke et al., 2002), and reconstructing the history of the scattered blocks and nappes exposed on the islands of the Aegean region (van Hinsbergen et al., 2005; Jolivet et al., 2013; Menant et al., 2016; Roche et al., 2018; Cordey and Quillévéré, 2020; Grasemann et al., 2021).

Mafic and ultramafic rocks are exposed on Rhodes as ophiolite bodies but are also present within an ophiolitic mélange unit called the Kopria Mélange (Fig. 2a). This mélange is composed of highly dismembered blocks of various ages split into two families with no clear understanding of their relationships: 1) Carboniferous to Early Cretaceous sedimentary rocks and 2) Middle Jurassic-Late Cretaceous ophiolitic rocks. The link between the Kopria Mélange and the Rhodes ophiolite is also not well understood. In this context, this study aims to review the ages and nature of these blocks to track their potential sources and to test the hypothesis that the siliceous sedimentary rocks of the Kopria Mélange may represent elements of the sedimentary cover of the ophiolites. At a wider scope, the goal is to improve our understanding of the relationships between mélanges and ophiolites in the Aegean and Eastern Mediterranean regions.

GEOLOGICAL SETTING

The island of Rhodes

The island of Rhodes is composed of a nappe pile characterized by continental margin to oceanic successions (Mutti et al., 1970; Leboulenger and Matesco, 1975; Harbury and Hall, 1988; Lekkas et al., 2007; Koepke et al., 2002; Garzanti et al., 2005) with the following units (Fig. 2a): metamorphic carbonates of the Lindos series (Cretaceous-Eocene), slope carbonates of the Ataviros Group (Late Jurassic-Eocene), platform carbonates of the Archangelos Group (Late Triassic-Paleocene), pelagic limestones and minor radiolarites of the Prophitis Ilias Unit (Late Triassic-Late Cretaceous), various sedimentary and ophiolitic rocks forming the Kopria Mélange (Carboniferous-Cretaceous) and, on top of the nappe pile, ophiolite bodies including serpentinite, gabbro, plagiogranite, dolerite and basalt (Late Cretaceous). The Prophitis Ilias Unit has been interpreted as the easternmost extension of the Pindos Zone *s.l.* of continental Greece, Peloponnesus and Crete (Orombelli and Pozzi, 1967; Aubouin and Dercourt, 1970; Danelian et al., 2001; Ozsvárt et al., 2017). This nappe pile is overlain by a postorogenic sedimentary succession with Oligocene to late Pleistocene ages (Katavia and Vati groups, Levantinian and Sgourou formations). All these units have been affected by Cenozoic faulting related to Aegean extension and movements along the forearc (Fig. 1).

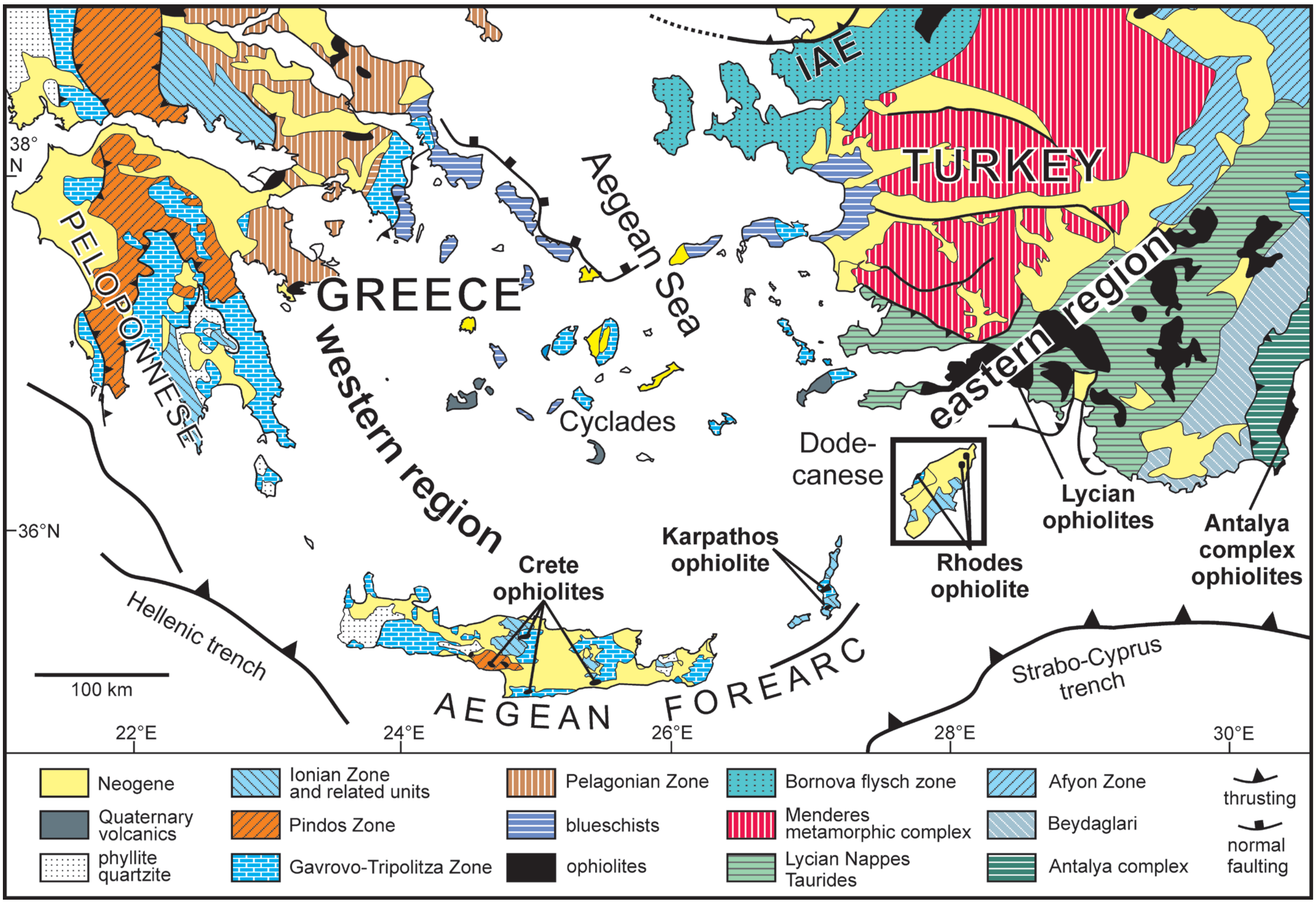

Fig. 1 - Structural map of the southern Aegean region with location of the island of Rhodes (black frame) and the distribution of ophiolites in southern Greece and western Turkey. Modified after Cordey and Quillévéré (2020) from data compiled from Bornovas and Rontogianni-Tsiabaou (1983), Jolivet et al. (2004; 2013), van Hinsbergen et al. (2005; 2010), Ersoy et al. (2014), and Gürer et al. (2018); reproduced with permission from Cambridge University Press. The 'eastern' and 'western' ophiolite regions refer to the classification by Robertson (2002). IAE: Izmir-Ankara-Erzincan Suture Zone.

Rhodes ophiolite

Ophiolitic rocks are exposed at several locations on the island of Rhodes (Fig. 2a), mostly cropping out as masses of highly sheared serpentinites ranging in size from meters to several hundred meters and are intruded by dolerite dikes. These rocks were originally described by Foullon (1891), Bukowski (1899), Martelli (1913), Vinassa de Regny (1922), Panagos (1967) and Mutti et al. (1970). More recently, some mafic rocks have been dated with K-Ar isotopic ages on hornblende grains extracted from intrusive dolerites at four localities (Wrissa, Louka, Speriolis, Kritinia; Koepke et al., 2002). The ages range between 90.8±2.4 and 87.3±2.8 Ma (late Turonian-early Santonian; Cohen et al., 2013), with the exception of one younger age of 74.5±2.2 Ma (late Campanian-early Maastrichtian, Koepke et al. 2002). Similar Late Cretaceous ages were obtained from the ophiolite on the nearby island of Karpathos (Koepke et al., 2002) although some of these K-Ar ages were recently questioned in relation to the occurrence of Early Cretaceous radiolarian chert in stratigraphic contact with the magmatic rocks (Cordey and Quillévéré, 2020).

The Kopria Mélange

The Kopria Mélange is composed of a volcano-sedimentary matrix with blocks of sedimentary and ophiolitic rocks (Mutti et al., 1970; Leboulenger and Matesco, 1975; Hatzipanagiotou, 1987; 1988) exposed in the northwestern part of the island near Mandriko and Kritinia (Fig. 2b). This unit was first described by Migliorini (1925) and Migliorini and Desio (1931), who considered it a distinct unit from the ophiolites. The name "Kopria diabases-radiolarites" was then proposed by Mutti et al. (1970) based on the two dominant lithologies. These authors established a type locality to the southwest of Kopria Bay (Fig. 2b) where the mélange is exposed with a thickness of 60 m. The term "Kopria Mélange" has more recently been used in studies focusing on the faunal content of the limestone blocks (Garzanti et al., 2005; Ozsvárt et al., 2017).

As described and emphasized by Hatzipanagiotou (1988), the geomorphology of the Mandriko-Kritinia region is determined by Neogene neotectonics. Carbonates are preserved at higher tectonic levels and elevations than the mélange, which is exposed in low areas. A chaotic organization of clasts and blocks of very diverse sedimentary and magmatic lithologies and sizes are incorporated into a volcano-sedimentary matrix and locally reaches a thickness of 300 m. The sedimentary blocks are composed of a variety of carbonates including gray and white micritic, bioclastic, and cherty limestones, red radiolarites, sandstones and flysch. The blocks of ophiolitic rocks are composed of serpentinite, dolerite, gabbro and basalt. Scattered blocks of metamorphic rocks composed of marble, amphibolite, calcschist and schist. The matrix is composed of altered red schists and pyroclasts.

Several hypotheses have been proposed regarding the stratigraphic and tectonic relationships between the Kopria Mélange and the surrounding units (Fig. 3). It was first interpreted as the fragmentation of an older substratum affected by submarine eruptions leading to mixing with younger ophiolitic rocks (Mutti et al. 1970) and then interpreted as dismembered elements of the Profitis Ilias Unit (Aubouin and Dercourt, 1970; Leboulenger and Matesco, 1975; Garzanti et al., 2005; Ozsvárt et al., 2017) or a typical ophiolitic mélange (*sensu* Gansser, 1974, *i.e.*, a mixing of blocks of olistostromal and tectonic origins associated with an ophiolite belt) structurally overlain by the ophiolites (Hatzipanagiotou, 1988; 1991; Koepke et al., 2002). These discrepancies are related to the lack of coherent stratigraphy: the contact between the Kopria Mélange and the ophiolite is not exposed (Hatzipanagiotou, 1988), and all units have undergone intense polyphase tectonic deformation (Mutti et al., 1970; Leboulenger and Matesco, 1975; Hatzipanagiotou, 1988). In a typical geological setting, the mélange should be spatially associated with ophiolites at several locations. With the exception of small ophiolite exposures near Mandriko and Kritinia (Fig. 2b), this is not the case on Rhodes: the Kopria Mélange is restricted to the northwestern part of the island whereas the largest ophiolite masses are located in the northeastern region where no mélange is exposed (Fig. 2a).

Many studies have described and characterized mélanges found in orogenic belts worldwide, seeking to better understand their geodynamic history and significance (e.g., Hsü, 1968; 1974; Gansser, 1974; Cowan, 1974; Raymond, 1984; Wakabayashi, 2012; Wakita, 2015; Festa et al., 2019). In light of the most recent models, the Kopria Mélange exhibits the characteristics of a tectonic mélange (Cowan, 1974; Raymond, 1984; Festa et al. 2019), as shown by the occurrence of extensive tectonic contacts, phacoidal blocks and a locally ordered block-in-matrix fabric. However, the occurrence of blocks of very different ages ranging from the Carboniferous to the Cretaceous suggests the probable co-occurrence of exotic and native blocks, pointing to a polygenetic mélange in which pre-existing primary diagnostic features have been overprinted and reworked by tectonic processes (see Discussion).

Previous ages obtained for the blocks

Early studies documented that the limestone blocks of the Kopria Mélange in the type locality (Fig. 2b) were mostly Paleozoic in age. Migliorini and Desio (1931) reported a Late Carboniferous block dated with crinoid and brachiopod faunas, an age later revised to the Early Permian by Mutti et al.

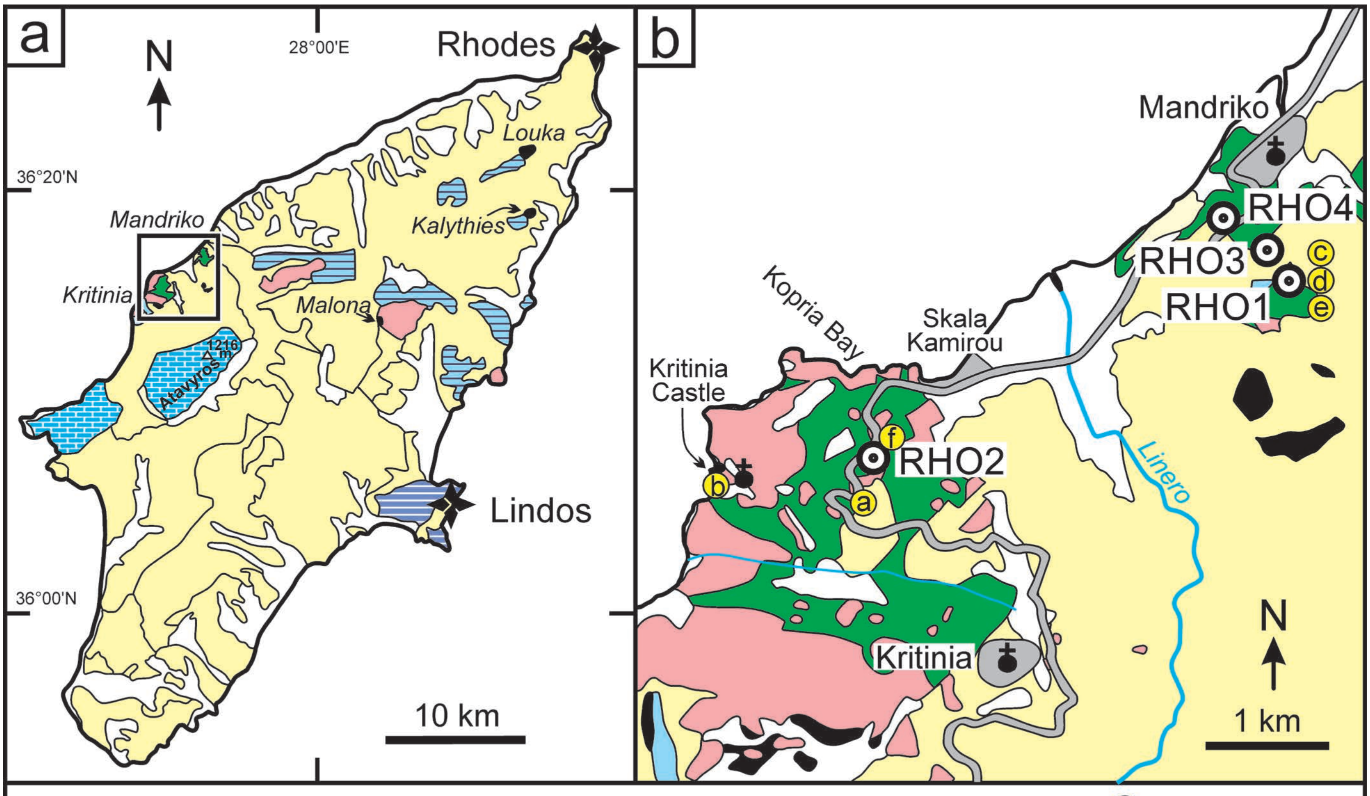

Fig. 2 - (a) Geological map and main units of Rhodes (modified after Mutti et al., 1970). (b) Geological map of the Mandriko-Kritinia area and location of the radiolarian localities RHO1 to RHO4 from the Kopria Mélange. Geology based on Mutti et al. (1970), Garzanti et al. (2005), and personal observations. Tr - K: Triassic-Cretaceous; Tr - T: Triassic-Tertiary.

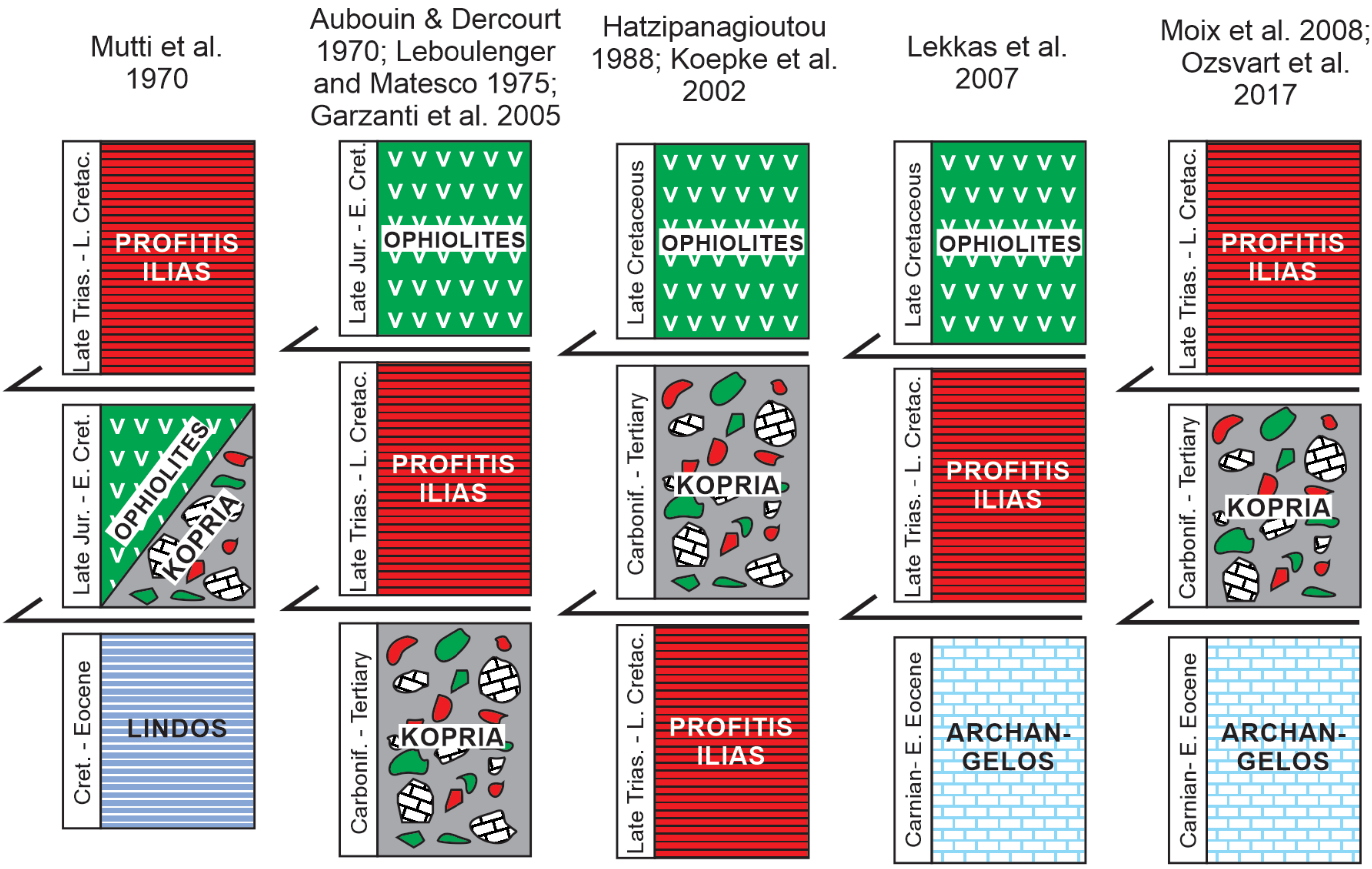

Fig. 3 - Previous interpretations of the structural relationships between the Kopria Mélange, the ophiolites and other units of the island of Rhodes (Aubouin and Dercourt, 1970; Mutti et al., 1970; Leboulenger and Matesco, 1975; Hatzipanagioutou, 1988; Koepke et al., 2002; Garzanti et al., 2005; Lekkas et al., 2007; Moix et al., 2008; Ozsvárt et al., 2017).

(1970). Three other blocks have been dated by Mutti et al. (1970) as middle Carboniferous, Late Carboniferous and Carboniferous-Permian based on foraminifers, brachiopods, crinoids and tetracorals. Leboulenger and Matesco (1975) also documented a block of gray-brown limestone of Late Carboniferous (late Moscovian) age based on foraminifers and algae. Garzanti et al. (2005) revisited some of the limestone blocks from the mélange and identified foraminifers, establishing Pennsylvanian and possibly Mississippian ages (late Visean-early Bashkirian, early Moscovian, and late Moscovian). The assemblages were interpreted as having tropical to subtropical Urals-Paleotethyan affinity, suggesting that the blocks may have been derived from the southernmost part of the northern Paleotethyan margin, and later accreted to the Hellenides. The occurrence of Carboniferous limestone blocks with similar fusulinids was reported within the Liri Unit of Evia (Stampfli et al., 2003; Garzanti et al., 2005). Other mélanges mark the Paleotethyan suture of the Hellenic realm (Pelagonian, Pindos, and Gavrovo-Tripolitza; De Bono et al., 1998, Stampfli et al., 2003).

The Kopria Mélange also contains blocks of Mesozoic sedimentary rocks. Leboulenger and Matesco (1975) described a sequence of red limestones of late Anisian or Carnian age based on foraminifers, which were interpreted as the stratigraphic base of the "diabases". More recently, a rich Carnian (Tuvalian) radiolarian assemblage was reported from a limestone block (Moix et al. 2008; Ozsvárt et al., 2017). To date, the youngest blocks of the mélange have been found by Hatzipanagiotou (1987), who documented Late Jurassic recrystallized limestones, Early Cretaceous (Berriasian) red micritic limestones, and various breccia-related clasts of bioclastic and fossiliferous limestones of early and late Early Cretaceous age.

The magmatic rocks from the Kopria Mélange have provided two sets of ages based on K-Ar geochronology (Hatzipanagiotou, 1991; Hatzipanagiotou and Tsikouras, 1999). Amphibolites from the Kritinia area range from ~ 180 to 160 Ma, an age fitting within the Toarcian-Oxfordian interval (Cohen et al., 2013), and microgabbros from the Kopria Bay area range from ~ 91 to 87 Ma, corresponding to the Turonian-Coniacian interval (Cohen et al., 2013). In summary, the Kopria Mélange contains two very distinct "families" of blocks, in terms of both their petrology and age: 1) sedimentary blocks of Early of early Late Carboniferous to Early Cretaceous age and 2) magmatic rocks of Middle Jurassic and Late Cretaceous ages.

The question of whether some of the blocks of the Kopria Mélange may represent the sedimentary cover of the Rhodes ophiolite has rarely been addressed, not only due to these age differences, but also due to the lack of stratigraphic contact between the sedimentary and ophiolitic rocks (Hatzipanagiotou, 1988). Leboulenger and Matesco (1975) suggested that some of the white limestone blocks could represent the sedimentary cover of some Kopria basalts. Hatzipanagiotou (1988) described carbonate layers associated with ultramafic rocks in Kaliethes near the main ophiolite body in the northeastern part of the island (Fig. 2a), but these layers are barren of diagnostic fossils.

MATERIALS AND METHODS

Along with reviewing the nature and ages of the blocks documented by previous investigations, this study targeted the radiolarian chert blocks associated with mafic and ultramafic rocks within the Kopria Mélange exposed near Mandriko and Kritinia (Fig. 2b). To maximize the quality of the microfossils, the samples were selected with specific field detection techniques applied to cherts from ophiolites and suture zones, using a strong hand lens (×25) and investigating specific microfacies, such as argillaceous layers within the chert beds (Cordey and Krauss, 1990; Cordey and Bailly, 2007). Radiolarians were then extracted by repetitive leaching of samples with low-concentration hydrofluoric acid (HF), handpicked and mounted on aluminum stubs for scanning electron microscope observation and taxonomic identifications (Phenom ProX Tabletop SEM, Laboratoire de Géologie de Lyon).

Four blocks from the Kopria Mélange contained identifiable radiolarian faunas. A selection of field views is presented in Fig. 4, documenting the general tectonic style and the rock units of the mélange (Fig. 4a, c, e, f) along with a selection of the sample localities (Fig. 4c-f).

– RHO1 is located on a gravel road near Mandriko, 700 m to the south of the coastal highway (Fig. 2b). This locality shows a mixture of altered basalts and serpentinites along with white limestones in tectonic contact with mafic rocks (dolerite and basalt) (Fig. 4c-e). This limestone unit is composed of beds 15 to 20 cm in thickness and is interlayered with nodular red chert beds. Radiolarians are

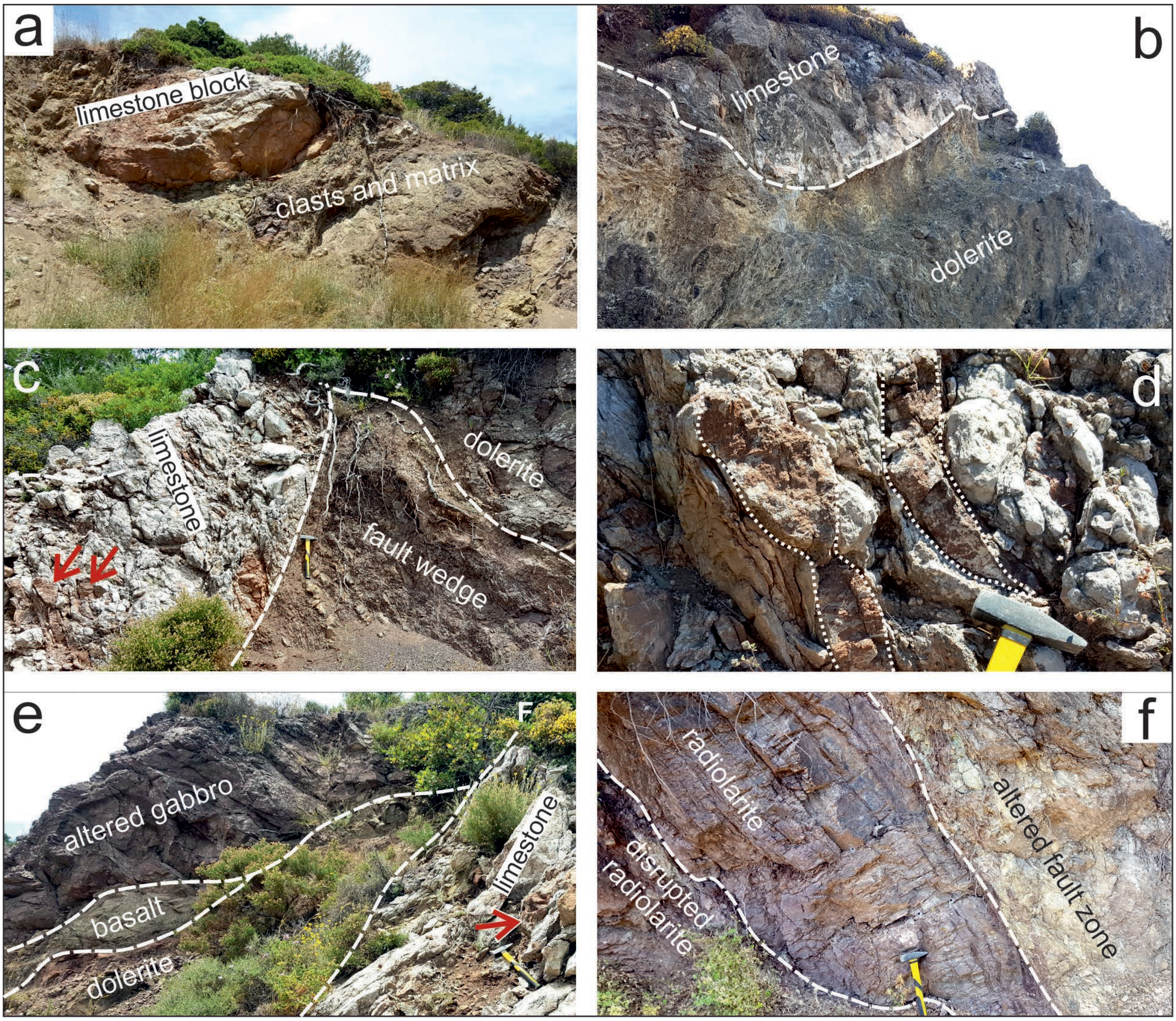

Fig. 4 - Field views of the Kopria Mélange and selected radiolarian localities (see Fig. 2b for locations of photographs). (a) Limestone block of unknown age (~ 2 m thickness) within a matrix comprising clasts of sedimentary and magmatic rocks of various sizes. (b) Dolerite and micritic limestone in stratigraphic contact ("Kritinia Castle section"; Leboulenger and Matesco, 1975). NB: this locality is not mapped as being part of the Kopria Mélange but as a tectonic slice of the ophiolite (age unknown). (c) Chert-bearing limestone of early Aalenian age in tectonic contact with dolerite, locality RHO1 (arrows: red chert nodular beds). (d) Close-up of red chert interbedded with limestone, locality RHO1 (arrows in (c)). (e) Cherty limestone in tectonic contact with altered gabbro, basalt and dolerite near locality RHO1 (arrow: lenticular bed of red chert). (f) Isolated radiolarite sequence of late Kimmeridgian age in tectonic contact with surrounding units within the Kopria Mélange, locality RHO2.

present in the carbonate facies but are better preserved in the red chert, which was therefore favoured for sampling.

- RHO2 is located in the Kopria Mélange type area near Kopria Bay on a gravel road, approximately 40 m to the southeast of the highway (Fig. 2b). It is composed of one meter of red radiolarian bedded cherts in tectonic contact with the surrounding units (Fig. 4f).
- RHO3 is located in the Mandriko area (Fig. 2b). It is a small outcrop of red cherts located on a gravel road 500 m from the coastal highway. No other outcrops are visible in the immediate vicinity.
- RHO4 is located along the coastal highway 500 m to the northwest of Mandriko (Fig. 2b). It is an isolated outcrop of radiolarian cherts in an area where serpentinites are also present, but no contact is exposed.

RESULTS

Radiolarian taxa from this study are listed in Table 1. A selection of diagnostic radiolarians is presented in Fig. 5.

The sample RHO1 comprises 9 identified taxa (Table 1, Fig. 5): *Hexasaturnalis hexagonus* (Yao), *Hexasaturnalis tetraspinus* (Yao), *Hsuum* sp. cf. *H. matsuokai* Isozaki & Matsuda, *Parahsuum longiconicum* Sashida, *Parahsuum simplum* Yao, *Parahsuum* ? sp. cf. *P.* ? *magnum* Takemura, *Praeconocaryomma* sp. cf. *P. decora* Yeh, *Triactoma jakobsae* Carter, and *Triactoma jonesi* (Pessagno). The co-occurrence of *Hexasaturnalis hexagonus* (Unitary Association Zone UAZ 1-4, Baumgartner et al., 1995), *Hexasaturnalis tetraspinus* (UAZ 1-6, Baumgartner et al., 1995; Unitary Association UA 35-41, Carter et al. 2010), *Parahsuum simplum*

Table 1- Radiolarian taxa and assemblages from the Kopria Mélange of Rhodes.

Taxa	RH01	RH02	RH03	RH04
Archaeodictyomitra vulgaris Pessagno				x
Archaeodictyomitra sp. aff. *A. vulgaris* Pessagno			x	
Archaeospongoprunum sp.		x		
Campanomitra pulchella (Rüst)				x
Campanomitra ? sp.			x	
Crococapsa sp.				x
Cryptamphorella ? sp.				x
Ditrabs sp.			x	
Emiluvia sp. cf. *E. ordinaria* Ozvoldova		x		
Emiluvia sp.			x	
Eoxitus sp. cf. *E. dhimenaensis* (Baumgartner)		x		
Hexasaturnalis hexagonus (Yao)	x			
Hexasaturnalis tetraspinus (Yao)	x			
Holocryptocanium astiensis Pessagno			x	
Holocryptocanium sp.			x	
Hsuum sp. cf. *H. matsuokai* Isozaki & Matsuda	x			
Mirifusus guadalupensis Pessagno		x		
Mirifusus sp. cf. *M. guadalupensis* Pessagno		x		
Obesacapsula verbana (Parona)		x		
Parahsuum longiconicum Sashida	x			
Parahsuum simplum Yao	x			
Parahsuum ? sp. cf. *P.* ? *magnum* Takemura	x			
Paronaella sp. cf. *P. bandyi* Pessagno		x		
Praeconocaryomma sp. cf. *P. decora* Yeh	x			
Pseudodictyomitra sp.			x	
Spinosicapsa sp.			x	
Svinitzium sp.				x
Thanarla pulchra (Squinabol)			x	
Thanarla sp.			x	
Transhsuum sp. cf. *T. maxwelli* (Pessagno)		x		
Triactoma jakobsae Carter	x			
Triactoma jonesi (Pessagno)	x			
Triactoma sp.			x	
Xitus sp.			x	x
Zhamoidellum sp.		x		

Samples RHO1 to RHO4: see text.

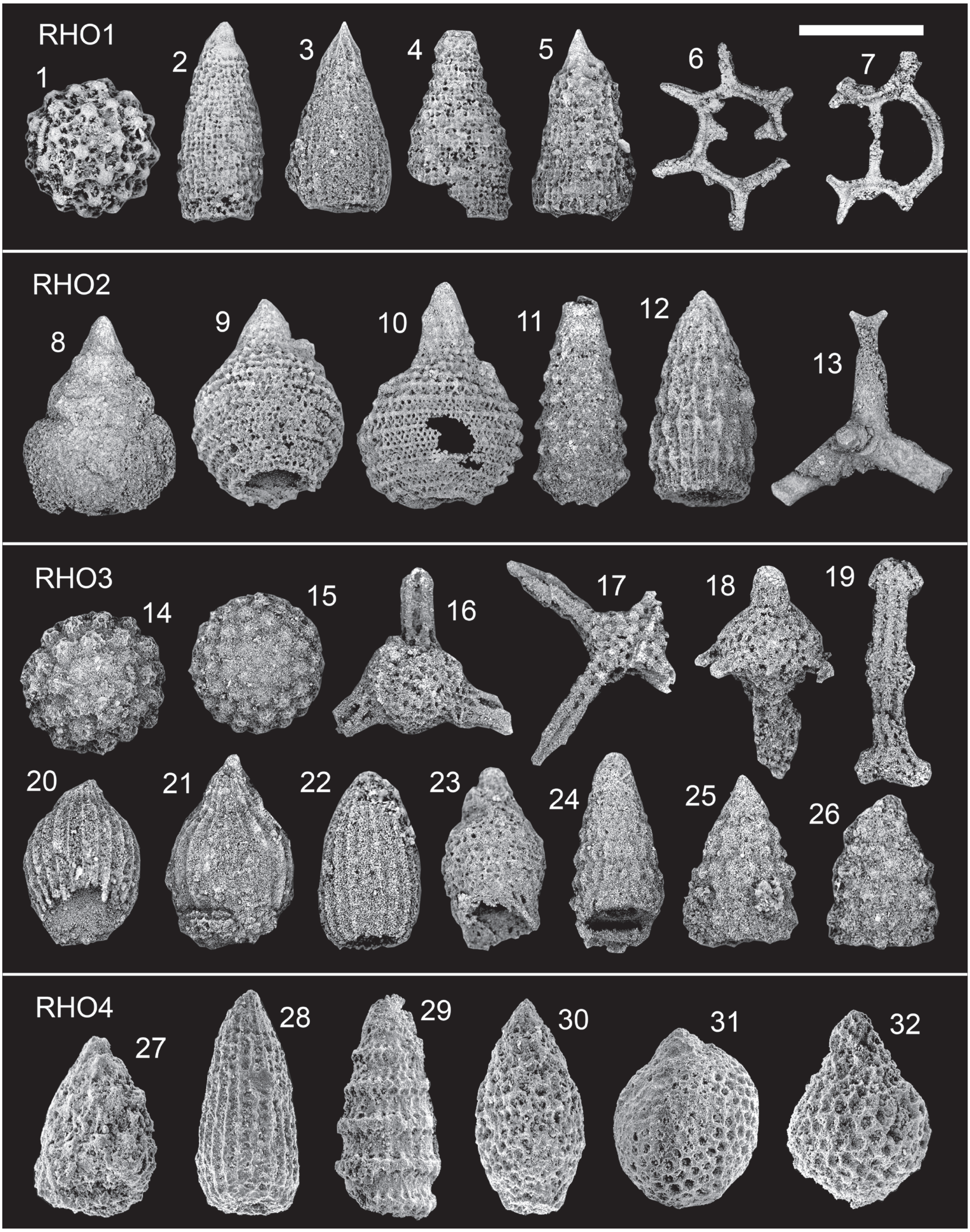

Fig. 5 - Scanning electron microphotographs (SEM) of radiolarian taxa from the Kopria Mélange (samples RHO1 to RHO4). For each picture: radiolarian taxon, scale length. RHO1: 1. *Praeconocaryomma* sp. cf. *P. decora* Yeh, 230 µm; 2. *Parahsuum simplum* Yao, 160 µm; 3. *Hsuum* sp. cf. *H. matsuokai* Isozaki & Matsuda, 160 µm; 4. *Parahsuum* ? sp. cf. *P. magnum* Takemura, 180 µm; 5. *Parahsuum longiconicum* Sashida, 140 µm; 6. *Hexasaturnalis hexagonus* (Yao), 220 µm; 7. *Hexasaturnalis tetraspinus* (Yao), 290 µm.RHO2: 8. *Obesacapsula verbana* (Parona), 250 µm; 9. *Mirifusus* sp. cf. *M. guadalupensis* Pessagno, 230 µm; 10. *Mirifusus guadalupensis* Pessagno, 230 µm; 11. *Eoxitus* sp. cf. *E. dhimenaensis* (Baumgartner), 170 µm; 12. *Transhsuum* sp. cf. *T. maxwelli* (Pessagno), 160 µm; 13. *Paronaella* sp. cf. *P. bandyi* Pessagno, 170 µm. RHO3: 14. *Holocryptocanium astiensis* Pessagno, 170 µm; 15. *Holocryptocanium* sp., 170 µm; 16. *Triactoma* sp., 170 µm; 17. *Emiluvia* sp., 270 µm; 18. *Spinosicapsa* sp., 190 µm; 19. *Ditrabs* sp., 240 µm; 20. *Thanarla* sp., 130 µm; 21. *Thanarla pulchra* (Squinabol), 140 µm; 22. *Archaeodictyomitra* sp. aff. *A. vulgaris* Pessagno, 120 µm; 23. *Campanomitra* ? sp., 150 µm; 24. *Pseudodictyomitra* sp., 160 µm; 25-26. *Xitus* sp., 160 µm. RHO4: 27. *Xitus* sp., 180 µm; 28. *Archaeodictyomitra vulgaris* Pessagno, 110 µm; 29. *Svinitzium* sp., 110 µm; 30. *Campanomitra pulchella* (Rüst), 100 µm; 31. *Cryptamphorella* ? sp., 110 µm; 32. *Crococapsa* sp., 120 µm.

(UA 1-36, Carter et al. 2010), *Parahsuum longiconicum* (UA 10-35, Carter et al., 2010) and *Triactoma jakobsae* (UAZ 1-4, Baumgartner et al., 1995; UA 32-41, Carter et al., 2010) shows that this assemblage is Aalenian in age. A more precise correlation points to the UA 35 (Carter et al., 2010), a component of the *Higumastra transversa - Napora nipponica* Zone of early Aalenian age (Carter et al., 2010).

The sample RHO2 is composed of eight radiolarian taxa (Table 1, Fig. 5): *Archaeospongoprunum* sp., *Emiluvia* sp. cf. *E. ordinaria* Ozvoldova, *Eoxitus* sp. cf *E. dhimenaensis* (Baumgartner), *Mirifusus guadalupensis* Pessagno, *Mirifusus* sp. cf. *M. guadalupensis* Pessagno, *Obesacapsula verbana* (Parona), *Paronaella* sp. cf. *P. bandyi* Pessagno, *Transhsuum* sp. cf. *T. maxwelli* (Pessagno) and *Zhamoidellum* sp.. The co-occurrence of *Mirifusus guadalupensis* (UAZ 5-11, Baumgartner et al. 1995), *Obesacapsula verbana* (UAZ 11-20, Baumgartner et al., 1995) and *Transhsuum* (genus ranges from the early Pliensbachian to the late Kimmeridgian, O'Dogherty et al., 2009) indicates that this assemblage is late Kimmeridgian in age.

The assemblage of sample RHO3 is fairly diverse and comprises twelve taxa (Table 1, Fig. 5): *Archaeodictyomitra* sp. aff. *A. vulgaris* Pessagno, *Campanomitra* ? sp., *Ditrabs* sp., *Emiluvia* sp., *Holocryptocanium astiensis* Pessagno, *Holocryptocanium* sp., *Pseudodictyomitra* sp., *Spinosicapsa* sp., *Thanarla pulchra* (Squinabol), *Thanarla* sp., *Triactoma* sp., *Xitus* sp.. The co-occurrence of the genera *Emiluvia* (early Sinemurian-late Valanginian) and *Holocryptocanium* (early Valanginian-late Coniacian) indicates that the assemblage is Valanginian in age (O'Dogherty et al., 2009). The known ages of the other taxa of the assemblage are compatible with this age establishment, for instance *Thanarla pulchra* (UAZ 15-22, Baumgartner et al., 1995).

The sample RHO4 comprises six identified taxa (Table 1, Fig. 5): *Archaeodictyomitra vulgaris* Pessagno, *Campanomitra pulchella* (Rüst) (a species formerly attributed to the genus *Stichocapsa* which is *nomen dubium*; O'Dogherty et al., 2009), *Crococapsa* sp., *Cryptamphorella* ? sp., *Svinitzium* sp. and *Xitus* sp.. This assemblage is moderately preserved and has only two identified species, *Archaeodictyomitra vulgaris* Pessagno (Subzone 5C to Zone 6, late Valanginian to late Aptian; Pessagno, 1977) and *Campanomitra pulchella* (Rüst) (UAZ 17-22; late Valanginian to late Barremian-early Aptian; Baumgartner et al., 1995). The other morphotypes are identified at the generic level only. Among them, the common age range of *Crococapsa* sp., *Svinitzium* sp. and *Xitus* sp. is late Tithonian-late Aptian. Overall, the age of sample RHO4 is located within the interval late Valanginian-early Aptian.

DISCUSSION

Age and origin of Kopria radiolarian chert-bearing blocks

In summary, the studied radiolarian chert-bearing blocks in the Kopria Mélange are Middle Jurassic (early Aalenian), Late Jurassic (late Kimmeridgian), and Early Cretaceous (Valanginian; late Valanginian-early Aptian) in age (Fig. 6). These results confirm the occurrence of Mesozoic blocks in the Kopria Mélange previously established by Hatzipanagiotou (1987) and provide more precision on the Late Jurassic and Early Cretaceous ages. Overall, they complement the set of results obtained from the carbonate blocks (Migliorini and Desio, 1931; Mutti et al., 1970; Leboulenger and Matesco, 1975; Hatzipanagiotou, 1987; Garzanti et al., 2005; Ozsvárt et al., 2017). The total age range represented by the sedimentary strata from blocks of the mélange now spans from the Early or early Late Carboniferous (late Visean-early Bashkirian, ~ 335-321 Ma) to the Early Cretaceous (late Valanginian-early Aptian, ~ 134-122 Ma) (Fig. 6).

The radiolarian data suggest a correlation of the younger blocks in the mélange with some members of the Prophitis Ilias Unit (Fig. 2):

- The early Aalenian block (RHO1, Fig. 4c) has a lithology that is similar to the Jurassic cherty limestones described by Mutti et al. (1970) and Leboulenger and Matesco (1975), such as those in the Malona section (Mutti et al., 1970) which is also called the Xerovourna section (Leboulenger and Matesco, 1975; "*calcaires marneux à silicifications rouges"*: marly limestones with red silicifications) (Fig. 6).
- There is a strong lithological affinity between the radiolarite block of late Kimmeridgian age (RHO2, Fig. 4f) and the radiolarite member of the Prophitis Ilias Unit, which was dated as Middle Jurassic (?) to Oxfordian by Danelian et al. (2001). The late Kimmeridgian block could correspond to the middle part of the radiolarite member (Fig. 6).
- Valanginian and late Valanginian-early Aptian ages are found within the chert beds which could be related to the Early Cretaceous cherty limestones of the Prophitis Ilias Unit. These rocks are also described in the Malona/Xerovourna section by Mutti et al. (1970) and Leboulenger and Matesco (1975) as radiolarian-bearing siliceous marls with layers of radiolarian chert («"*marnes siliceuses à radiolaires avec quelques passées de jaspes à radiolaires*") (Fig. 6).

As mentioned earlier, the blocks of the Kopria Mélange are split into two distinct families: 1) sedimentary blocks with Carboniferous-Early Cretaceous ages and 2) magmatic rocks with Middle Jurassic and Late Cretaceous ages. The new radiolarian data confirm that the ages of the sedimentary rocks partly overlap with those of the magmatic rocks (Fig. 6). A spatial association of these rocks is common, as was stressed by Mutti et al. (1970) who used the name "Kopria diabases-radiolarites". These observations lead to a second hypothesis: some Kopria radiolarian cherts may represent disrupted elements of the sedimentary cover of the magmatic blocks in the mélange (Fig. 6). The early Aalenian cherty limestones (~174-170 Ma, Cohen et al., 2013) could be linked to magmatic rocks dated to ~ 180-160 Ma by Hatzipanagiotou (1988; 1991). Similarly, some of the younger cherty limestones could be the sedimentary cover of the Late Cretaceous mafic rocks (~ 91-87 Ma, Turonian-Coniacian interval; Hatzipanagiotou, 1991). At this point, it is difficult to confirm this hypothesis given the lack of stratigraphic contacts.

What type of mélange?

As mentioned earlier, the Kopria Mélange exhibits features of a tectonic mélange (Raymond, 1984; Festa et al. 2019), including extensive tectonic contacts (*i.e.*, Fig. 4c, e), phacoidal blocks and a locally ordered block-in-matrix fabric (Fig. 4a). However, the co-occurrence of potentially exotic and native blocks also suggests a polygenetic mélange in which the primary diagnostic features have been overprinted and reworked by tectonic processes (Ghikas et al. 2010; Festa et al., 2019). The mixing of blocks of potentially olistostromal and tectonic origins (Fig. 4a, c, e, f) and the close association with an ophiolite belt along the Aegean forearc (Fig. 1) also point to the definition of Gansser (1974) of an

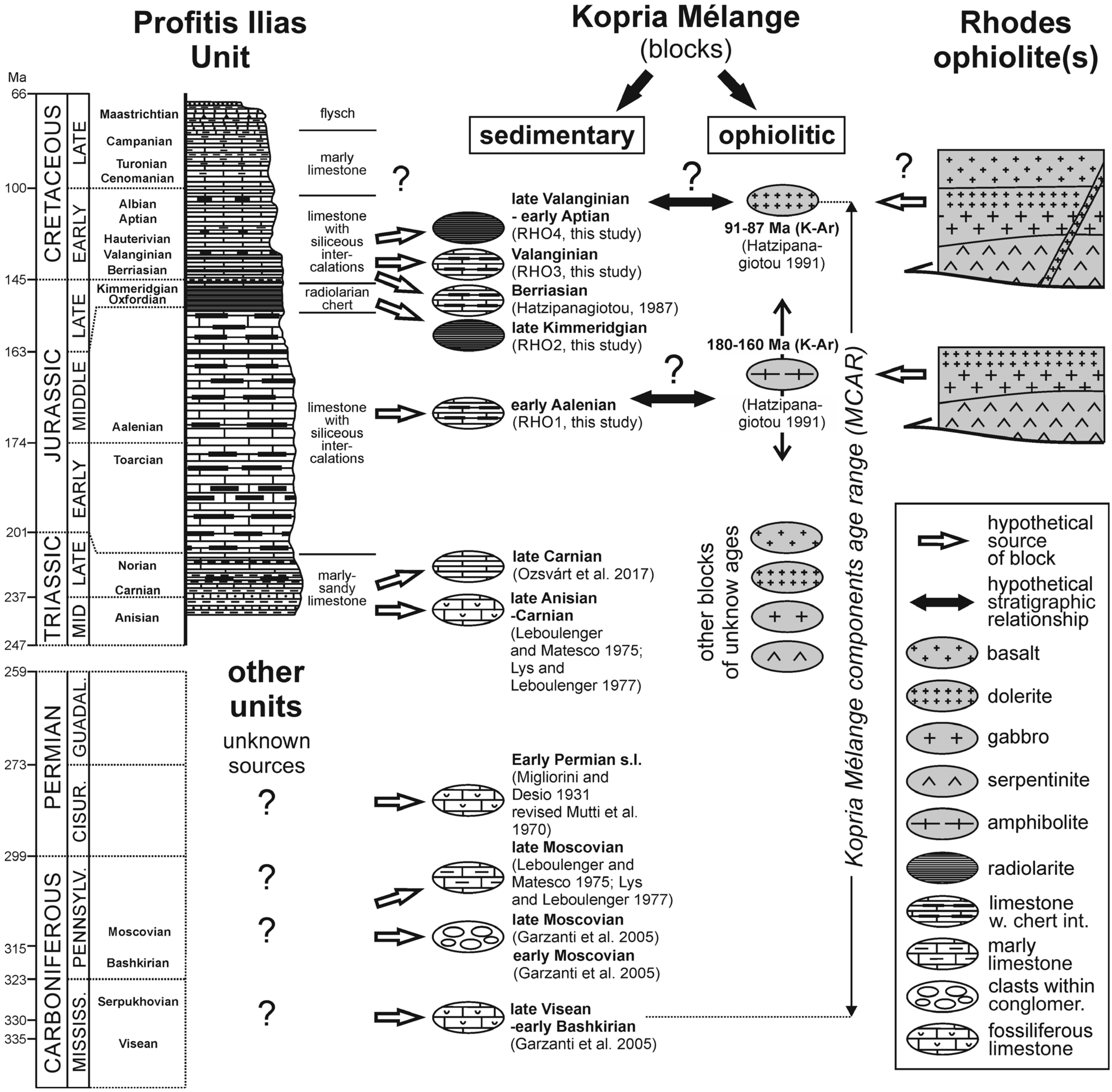

Fig. 6 - Synthesis of ages obtained on the blocks of the Kopria Mélange from previous authors and from this study, showing potential correlations with the Prophitis Ilias Unit and/or the Rhodes ophiolite. The reconstruction of Rhodes ophiolite is based on the occurrence of the different magmatic rock types on the island but is speculative. The Kopria Mélange components age range ("MCAR") spans from the Middle-Late Carboniferous (late Visean-early Bashkirian, ~ 335-321 Ma; foraminifer biochronology; Garzanti et al., 2005) to 91-87 Ma (K-Ar geochronology on dolerite; Hatzipanagiotou, 1991), representing 239 ± 9 million years (see text).

ophiolitic mélange which is formed by the obduction of ophiolitic material onto continental plates related to convergence and the disappearance of the transition zone continent/ocean, and is characterized by the association of sedimentary rocks from different environments (platform, slope and deep basin), along with ophiolitic components. A more recent model proposed the concept of an ocean plate stratigraphy (OPS) mélange (Wakita, 2015) resulting from the fragmentation, disruption and mixing of primary lithostratigraphic successions of the subducting ocean plate. The younger elements of the Kopria Mélange such as the radiolarite-basalt-dolerite association outlined as the so-called Kopria diabases-radiolarites (Mutti et al., 1970) could match the limestone-basalt and serpentinite-basalt-chert types of the OPS mélange (Wakita, 2015). The characterization of the Kopria Mélange is probably incomplete and requires more precise mapping and complementary analytical studies, including magmatic ages and metamorphic grades, to better identify the stratigraphic and structural levels sampled by décollement/shear zone surfaces.

However, this study indicates that the chronological heterogeneity of the Kopria blocks is greater than previously thought, as revealed by the age discrepancies and the juxtaposition of diachronous blocks. This shows the limitations of some mélange models that focus mostly on physical criteria but do not take much into account the ages of the different components within a mélange, therefore underestimating the duration of the sedimentary and tectonic processes involved. These protracted events have significant geodynamic consequences, for instance in the case of long-lived subduction-accretion processes (Cordey and Schiarizza, 1993). Therefore, a complementary time criterion could be added to the "toolbox" of mélange studies: the mélange components age range (MCAR) corresponding to the time span represented by all elements in a given mélange (blocks and matrix). In the case of the Kopria Mélange, the MCAR spans from the Early or early Late Carboniferous (late Visean-early Bashkirian based on foraminifers: ~ 335-321 Ma; Garzanti et al., 2005) to 91-87 Ma (K-Ar geochronology on dolerite; Hatzipanagiotou, 1991). Taking into account the margins of error, the Kopria Mélange MCAR corresponds, so far as known, to a minimum of 230 Myr (= 321-91 Ma) and a maximum of 248 Myr (= 335-87 Ma), i.e., 239±9 Myr (Fig. 6), a significant duration more compatible with a polygenetic ophiolitic mélange rather than with a strictly tectonic or short-lived OPS mélange.

Comparisons along the Aegean forearc (Karpathos, Crete)

Along the Aegean forearc, ophiolitic rocks are also exposed on the island of Karpathos located 100 km to the southwest of Rhodes (Fig. 1), where they form relatively small exposures of serpentinized peridotites with minor occurrences of gabbros and dolerite dikes ("dismembered type" *sensu* Coleman, 1977). These rocks lie within tectonic slices at the top of a nappe pile exposed in the central part of the island and belong to a tectono-stratigraphic succession described as the Xindothio Unit (Davidson-Monett, 1974; Aubouin et al., 1976; Hatzipanagiotou, 1987). Mafic and ultramafic rocks are commonly found in tectonic contact with the underlying units, but the radiolarites depositionally overlie the ophiolites at several locations and are overlain by a succession of Cretaceous limestones with, locally, some relatively good stratigraphic continuity (Davidson-Monett, 1974; Aubouin et al., 1976; Hatzipanagiotou, 1987, 1988; Cordey and Quillévéré, 2020).

In Karpathos, K-Ar isotope ages were obtained from magmatic rocks at two locations (Koepke et al., 1985; Hatzipanagiotou, 1991; Koepke et al., 2002). In Lastos, ages range between 84.7 and 79.6 Ma, encompassing the middle Santonian-middle Campanian interval (Cohen et al., 2013). In Menetes, the isotopic ages range between 99.5 and 88.4 Ma, corresponding to the middle Cenomanian-middle Coniacian interval. These ages are similar to those obtained for the Rhodes ophiolite (between 90.8±2.4 and 87.3±2.8 Ma, Koepke et al., 2002). However, in Karpathos, the Early Cretaceous ages obtained for the radiolarian cherts and cherty limestones in stratigraphic contact with ophiolitic rocks suggest that some isotopic ages might have been reset by Late Cretaceous metamorphism and that these rocks may have formed during the Early Cretaceous (Albian). In addition, the Kopria Mélange of Rhodes is totally devoid of the stratigraphic continuity observed in the Xindothio Unit of Karpathos. The ages of the radiolarian faunas in blocks in the Kopria Mélange (early Aalenian, late Kimmeridgian, Valanginian, and late Valanginian-early Aptian) are also older than those of the Xindothio Unit (Aptian, Albian, Turonian).

Farther west along the forearc, ophiolites are also exposed in Crete (Fig. 1) where K-Ar isotope ages range from 160 to 140 Ma (Middle-Late Jurassic; Koepke et al. 2002; Liati et al. 2004). This age is slightly younger than the K-Ar isotope age of ~ 180 to 160 Ma obtained from one block in the Kopria Mélange (Hatzipanagiotou, 1991; Hatzipanagiotou and Tsikouras, 1999). A closer correlation can be made between the Cretan radiolarites and the Prophitis Ilias radiolarites of Rhodes whose ages partly overlap during the Late Jurassic (Danelian et al., 2001; Stampfli et al., 2010). These units are interpreted as having an affinity with the Pindos Zone *s.l.* of continental Greece and Peloponnesus (Orombelli and Pozzi, 1967; Aubouin and Dercourt, 1970; Danelian et al., 2001; Tortorici et al., 2012; Ozsvárt et al., 2017).

Comparisons with Turkish ophiolites

Previous authors noted great similarities in both petrography and trace elements between the mafic and ultramafic rocks of Karpathos and Rhodes and those of western Turkey, including the occurrence of ophiolitic mélanges (Hatzipanagiotou, 1988), with emphasis on the depleted nature of the peridotites and the geochemistry of the dikes, which are typical of supra-subduction zone ophiolites (Koepke et al., 2002). Stratigraphic similarities can be found within the Lycian Nappes (Figs. 1, 7) (de Graciansky, 1967; Collins and Robertson, 1997, 2003; Dilek et al., 1999; Robertson, 2002; Schmid et al., 2020) and more specifically in the Lycian Mélange, which is located less than 100 km to the northeast of the Kopria Mélange of Rhodes. The Lycian Mélange is composed of dismembered thrust sheets and detached blocks of pelagic limestones with thin sequences of highly disrupted radiolarites, overlain by blocks and thrust sheets of serpentinized harzburgites, gabbros, dolerites and basalts together with smaller blocks of radiolarites and limestones (Collins and Robertson, 1997). It has been interpreted

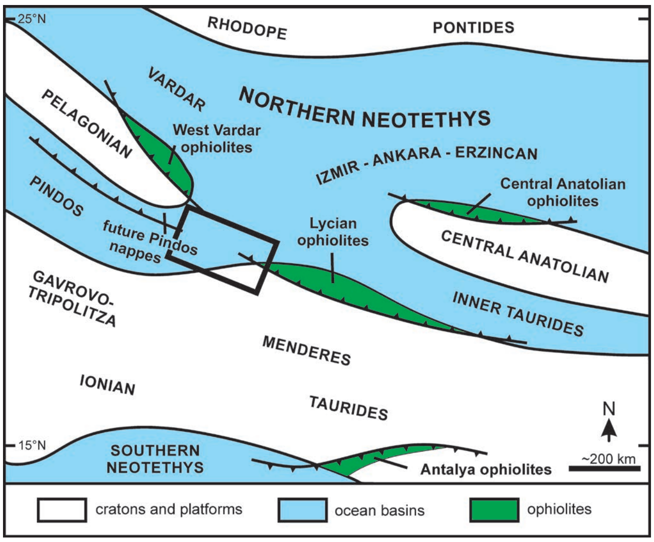

Fig. 7 - Schematic paleogeographic map of western Neotethyan basins in Cretaceous times (modified after Cordey and Quillévéré, 2020; reproduced with permission from Cambridge University Press). Compiled from Barrier and Vrielynck (2008), Robertson et al. (2012), Menant et al. (2016), Barrier et al. (2018), Maffione and van Hinsbergen (2018). Black rectangle: approximate position of Rhodes ophiolitic and sedimentary components presently recorded within the Kopria Mélange prior to obduction. Note that the ophiolites and the tectonic nappes depicted in the diagram have been emplaced diachronously: they just indicate the initial locations and relationships with the surrounding oceanic basins.

as an accretionary prism related to the subduction of Mesozoic Neotethyan oceanic crust (Collins and Robertson, 1997; 1999). Within the Lycian Mélange, Danelian et al. (2006) documented radiolarian cherts with Middle-Late Jurassic (Bajocian; Oxfordian-early Tithonian) and Early Cretaceous (Berriasian-early Hauterivian) ages. These ages are very similar to those obtained for the youngest segment of the Kopria Mélange of Rhodes (also Middle-Late Jurassic and Early Cretaceous).

Other Turkish units display pre-Late Cretaceous ages established from radiolarian chert sequences associated with mafic and ultramafic rocks. In the Marmaris ophiolites, the youngest sediments are pre-Cenomanian (Güngör et al., 2019). In the Central Sakarya Zone, the Dağküplü Mélange includes several slices of mid-ocean ridge metabasalts that alternate with radiolarites dated to the Middle-Late Jurassic (Bathonian-Tithonian), Early Cretaceous (Hauterivian-Aptian) and early Late Cretaceous (Cenomanian) (Göncüoğlu et al., 2000, 2001). Farther east in the Ankara Mélange, blocks of radiolarite associated with gabbros and pink micritic limestones are dated to the Late Triassic to Early Cretaceous (Bragin and Tekin, 1996). As in the Dağküplü Mélange, the youngest radiolarites of the Ankara Mélange are Cenomanian in age (Bragin and Tekin, 1996).

Many authors have established a link between the Lycian Nappes and the Izmir-Ankara-Erzincan Suture Zone (IAE; Figs. 1, 7) (Robertson and Pickett, 2000; Okay et al., 2001; Collins and Robertson, 2003; Robertson et al., 2004; van Hinsbergen et al., 2010, 2020). The IAE (Izmir-Ankara-Erzincan) Suture Zone is itself considered a remnant of the Northern Neotethyan Ocean (Danelian et al., 2006) and records a long history of radiolarite accumulation. The IAE Suture Zone may also be the source of the Karpathos and Rhodes ophiolites (Cordey and Quillévéré, 2020) as well as some of the Cretaceous blocks in the Kopria Mélange (this study).

A mélange recording two ophiolites?

The ophiolitic mélanges of Greece and westernmost Turkey (Vardar, Vourinos, Othris, Evia, Pindos, Crete, Karpathos, Rhodes, and Lycian Nappes) are spatially associated with ophiolites, as stressed by Hatzipanagiotou (1988), and in accordance with the model of Gansser (1974). Hatzipanagiotou (1988) proposed a tectono-sedimentary model to describe what led to the formation of the Kopria Mélange: a multiphase long-lived tectonic event starting with a shortening phase in the Hellenides during the Late Jurassic-Early Cretaceous, associated with unstable conditions leading to deformation on the edge of the basins and intense brecciation mixing ophiolites with a sedimentary base as old as the Carboniferous, leading to resedimentation of isolated blocks. However, in light of more recent models, it is difficult to determine whether the mélange was exclusively formed during obduction or was related to subduction-accretion processes associated with stacking of upper and lower plate components. Blocks of ophiolites and radiolarian cherts and/or cherty limestones could have been sampled from a downgoing slab of oceanic lithosphere (the OPS -type from Wakita, 2015), while blocks from continental paleomargin(s) involving Carboniferous to Cretaceous units (including Prophitis Ilias) were sampled from the upper plate. The mélange is postdated by the early Oligocene deposits of the Katavia flysch.

A complication also lies within the double magmatic signature of the Kopria Mélange which comprises Jurassic and Early-Late Cretaceous ophiolitic rocks (Fig. 6). This suggests that the island of Rhodes could represent the transition between units comprising Middle-Late Jurassic ophiolitic units traditionally associated with the Hellenides (Greece, Fig. 1) and Cretaceous ophiolitic units correlated with the Taurides (Turkey, Fig. 1), thus recording sources from two distinct and diachronous parts of the Northern Neotethyan basin.

CONCLUSION

This study documents the occurrence of radiolarian faunas of Middle Jurassic (early Aalenian), Late Jurassic (late Kimmeridgian), and Early Cretaceous (Valanginian; late Valanginian- early Aptian) ages within chert-bearing blocks of the Kopria ophiolitic mélange of Rhodes. On the one hand, these results suggest a correlation between the younger blocks of the mélange and the Prophitis Ilias Unit traditionally associated with the Pindos Zone *s.l.* of continental Greece, Peloponnesus and Crete. On the other hand, some of the Kopria blocks may represent disrupted elements of the sedimentary cover of magmatic rocks (Jurassic and Cretaceous in age). This double magmatic signature could materialize the transition between units comprising Middle-Late Jurassic ophiolite elements traditionally associated with the Hellenides and Cretaceous ophiolite elements correlated with the Taurides. The precise tectonic mechanism that brought these elements together has yet to be established. Resolving this issue will probably require a larger number of isotopic and biochronological ages within the mélange. Hypotheses could be tested by studying the spatial distribution of blocks and potential tectonic polarities.

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